Laser annealed in-situ P-doped Ge for on-chip laser source applications
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Ashwyn Srinivasan, Marianna Pantouvaki, Yosuke Shimura, Clement Porret, IMEC (Belgium); **Rik Van Deun,** Univ. Gent (Belgium); **Roger Loo,** IMEC (Belgium); **Dries Van Thourhout,** Univ. Gent (Belgium); **Joris Van Campenhout,** IMEC (Belgium)

ABSTRACT

Realization of a monolithically integrated on-chip laser source remains the holy-grail of Silicon Photonics. Germanium (Ge) is a promising semiconductor for lasing applications when highly doped with Phosphorous (P) and or alloyed with Sn [1, 2]. P doping makes Ge a pseudo-direct band gap material and the emitted wavelengths are compatible with fiber-optic communication applications. However, in-situ P doping with Ge2H6 precursor allows a maximum active P concentration of 6×1019 cm-3 [3]. Even with such active P levels, n++ Ge is still an indirect band gap material and could result in very high threshold current densities. In this work, we demonstrate P-doped Ge layers with active n-type doping beyond 1020 cm-3, grown using Ge2H6 and PH3 and subsequently laser annealed, targeting power-efficient on-chip laser sources.
The use of Ge2H6 precursors during the growth of P-doped Ge increases the active P concentration level to a record fully activated concentration of 1.3×1020 cm-3 when laser annealed with a fluence of 1.2 J/cm2. The material stack consisted of 200 nm thick P-doped Ge grown on an annealed 1 µm Ge buffer on Si. Ge:P epitaxy was performed with PH3 and Ge2H6 at 320oC. Low temperature growth enable Ge:P epitaxy far from thermodynamic equilibrium, resulting in an enhanced incorporation of P atoms [3]. At such high active P concentration, the n++ Ge layer is expected to be a pseudo-direct band gap material. The photoluminescence (PL) intensities for layers with highest active P concentration show an enhancement of 18× when compared to undoped Ge grown on Si as shown in Fig. 1 and Fig. 2. The layers were optically pumped with a 640 nm laser and an incident intensity of 410 mW/cm2. The PL was measured with a NIR spectrometer with a Hamamatsu R5509-72 NIR photomultiplier tube detector whose detectivity drops at 1620 nm. Due to high active P concentration, we expect band gap narrowing phenomena to push the PL peak to wavelengths beyond the detection limit (1620nm) of the setup. Therefore, the 18× enhancement is a lower limit estimation. In this contribution, an extensive study of laser annealing conditions and their impact on material properties will be discussed.
A major concern in using highly doped Ge as an active medium is the increase in free-carrier absorption (FCA). However, results reported in [4] suggest that FCA is significantly dominated by holes due to larger absorption cross-section of holes compared to electrons. The FCA results in [4] and JDOS modeling were used to calculate the gain spectrum for the highest doped Ge samples, including the typical 0.25% biaxial tensile strain of epitaxial Ge on Si. A carrier lifetime of 3 ns is required as shown in Fig. 3 for a target threshold current density of sub-20 kA/cm2 which represents at least tenfold reduction when compared to active P-doping level of 6×1019 cm-3. As a result, laser annealed highly doped Ge layers grown with Ge2H6 precursors are a promising approach for realizing a power efficient on-chip Ge laser source.